6 Global Positioning System (GPS) Survey Specifications

Survey specifications describe the methods and procedures needed to attain a desired survey accuracy standard. The specifications for Post Processed GPS Surveys described in Section 6A are based on Federal Geodetic Control Subcommittee (FGCS) standards. The FGCS standards and specifications have been modified to meet the specific needs and requirements for various types of first-order, second-order, third-order, and general-order GPS surveys typically performed by Caltrans. The specifications for Real Time Kinematic (RTK) GPS Surveys described in Section 6B are based on accepted California Department of Transportation standards. For complete details regarding accuracy standards, refer to Chapter 5, “Classifications and Accuracy Standards.”

Caltrans GPS survey specifications are to be used for all Caltrans-involved transportation improvement projects, including special-funded projects.

GPS surveying is an evolving technology. As GPS hardware and processing software are improved, new specifications will be developed and existing specifications will be changed. The specifications described in this section are not intended to discourage the development of new GPS procedures and techniques.

Note: Newly developed GPS procedures and techniques, which do not conform to the specifications in this chapter, may be employed for production surveys, if approved by the District/Region Survey Manager. Newly developed procedures shall be submitted to the Office of Land Surveys for distribution and review by other districts.

Note: The specifications in Section 6A, “Post Processed GPS Survey Specifications” are separate and distinct from the specifications in Section 6B, “Real-Time Kinematic (RTK) GPS Survey Specifications.”

6A Post Processed GPS Survey Specifications

6A.1 Methods

6A.1-1 Static GPS Surveys

Static GPS survey procedures allow various systematic errors to be resolved when high-accuracy positioning is required. Static procedures are used to produce baselines between stationary GPS units by recording data over an extended period of time during which the satellite geometry changes.

6A.1-2 Fast-static GPS Surveys

Fast-static GPS surveys are similar to static GPS surveys, but with shorter observation periods (approximately 5 to 10 minutes). Fast-static GPS survey procedures require more advanced equipment and data reduction techniques than static GPS methods. Typically, the fast-static GPS method should not be used for corridor control or other surveys requiring horizontal accuracy greater than first order.

6A.1-3 Kinematic GPS Surveys

Kinematic GPS surveys make use of two or more GPS units. At least one GPS unit is set up over a known (reference) station and remains stationary, while other (rover) GPS units are moved from station to station. All baselines are produced from the GPS unit occupying a reference station to the rover units. Kinematic GPS surveys can be either continuous or “stop and go”. Stop and go station observation periods are of short duration, typically under two minutes. Kinematic GPS surveys are employed where third-order or lower accuracy standards are applicable.

6A.1-4 OPUS GPS Surveys

The NGS On-line Positioning User Service (OPUS) allows users to submit individual GPS unit data files directly to NGS for automatic processing. Each data file that is submitted is processed with respect to 3 CORS sites. OPUS solutions shall not be used for producing final coordinates or elevations on any Caltrans survey, however OPUS solutions may be used as a verification of other procedures.

6A.2 Equipment

Post processed GPS surveying equipment generally consists of two major components: the receiver and the antenna.

6A. 2-1 Receiver Requirements

First-order, second-order, and third-order post processed GPS surveys require GPS receivers that are capable of recording data. When performing specific types of GPS surveys (i.e. static, fast-static, and kinematic), receivers and software shall be suitable for the specific survey as specified by the manufacturer. Dual frequency receivers shall be used for observing baselines over 9 miles in length. During periods of intense solar activity, dual frequency receivers shall be used for observing baselines over 6 miles in length.

6A.2-2 Antennas

Whenever feasible, all antennas used for a project should be identical. For vertical control surveys, identical antennas shall be used unless software is available to accommodate the use of different antennas. For first-order and second-order horizontal surveys, antennas with a ground plane attached shall be used, and the antennas shall be mounted on a tripod or a stable supporting tower. When tripods or towers are used, optical plummets or collimators are required to ensure accurate centering over marks. Fixed height tripods are required for third-order or better vertical surveys. The use of range poles and/or stake-out poles to support GPS antennas should only be employed for third-order horizontal and general-order surveys.

6A.2-3 Miscellaneous Equipment Requirements

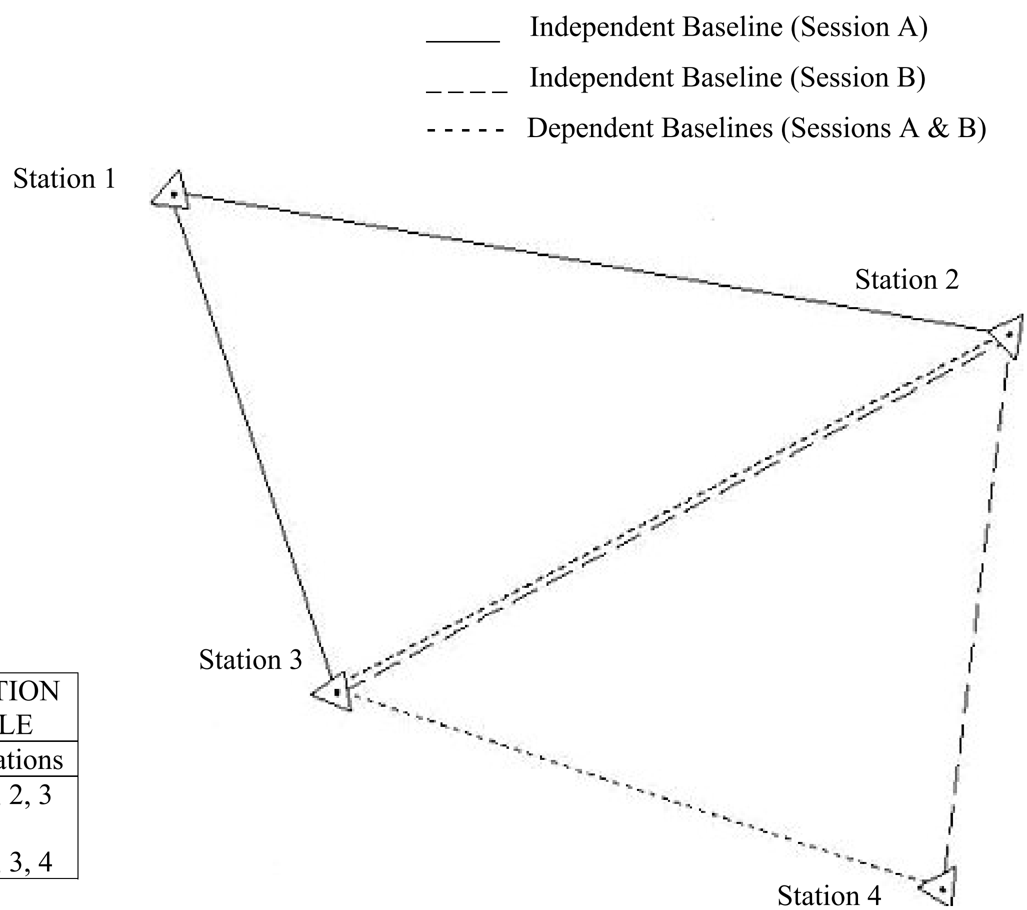
All equipment must be properly maintained and regularly checked for accuracy. Errors due to poorly maintained equipment must be eliminated to ensure valid survey results. Level vials, optical plummets, and collimators shall be calibrated at the beginning and end of each GPS survey. If the duration of the survey exceeds a week, these calibrations shall be repeated weekly for the duration of the survey. For details regarding equipment repair, adjustment, and maintenance, refer to Chapter 3, “Survey Equipment.”

6A.3 General Post Processed GPS Survey Specifications

6A.3-1 Network Design

Baselines (Vectors)

Baselines are developed by processing data collected simultaneously by GPS units at each end of a line. For each observation session, there is one less independent (non-trivial) baseline than the number of receivers collecting data simultaneously during the session. Notice in Figure 6A-1 that three receivers placed on stations 1, 2, and 3 for Session “A” yield two independent baselines and one dependent (trivial) baseline. Magnitude (distance) and direction for dependent baselines are obtained by separate processing, but use the same data used to compute the independent baselines. Therefore, the errors are correlated. Dependent baselines shall not be used to compute or adjust the position of stations.



OBSERVATION SCHEDULE	
Session	Stations
A	1, 2, 3
B	2, 3, 4

Figure 6A-1

Loops

A loop is defined as a series of at least three independent, connecting baselines, which start and end at the same station. Each loop shall have at least one baseline in common with another loop. Each loop shall contain baselines collected from a minimum of two sessions.

Networks

Networks shall only contain closed loops. Each station in a network shall be connected with at least two different independent baselines. Avoid connecting stations to a network by multiple baselines to only one other network station. First-order and second-order GPS control networks shall consist of a series of interconnecting closed-loop, geometric figures.

Redundancy

First-order, second-order, and third-order GPS control networks shall be designed with sufficient redundancy to detect and isolate blunders and/or systematic errors. Redundancy of network design is achieved by:

- Connecting each network station with at least two independent baselines
- Series of interconnecting, closed loops
- Repeat baseline measurements

Refer to tables 6A-1 through 6A-5 for the maximum number of baselines per loop, the number of required repeat independent baseline measurements, and least squares network adjustment specifications. Any Post-Processed GPS survey which lacks sufficient network or station redundancy to detect misclosures in an unconstrained (free) least squares network adjustment will be considered a general-order GPS survey.

Reference Stations

The reference (controlling) stations for a GPS Survey shall meet the following requirements:

- Same or higher order of accuracy as that intended for the project
- All on the NAD83 datum. See Chapter 4, "Survey Datums"
- All included in, or adjusted to, the California High Precision Geodetic Network (HPGN) with coordinate values that are current and meet reference network accuracy standards

- All of the same epoch, or adjusted to the same epoch using National Geodetic Survey (NGS) procedures
- Evenly spaced throughout the survey project and in a manner that no project station is outside the area encompassed by the exterior reference stations

Refer to tables 6A-1 through 6A-5 for the number and type of reference stations, and distances between stations.

Adjacent Station Rule (20 Percent Rule)

For first-order and second-order GPS surveys, an independent baseline shall be produced between stations that are closer than 20 percent of the total distance between those stations traced along existing or new connections. For example, in Figure 6A-2, if the distance between Station 5 and Station 1 is less than 20 percent of the distance between Station 1 and Station 3 plus the distance between Station 3 and Station 5, an independent baseline should be produced between Station 1 and Station 5. If the application of the adjacent station rule is not practical, an explanation shall be included in the survey notes and/or project report.

Direct connections shall also be made between adjacent intervisible stations.

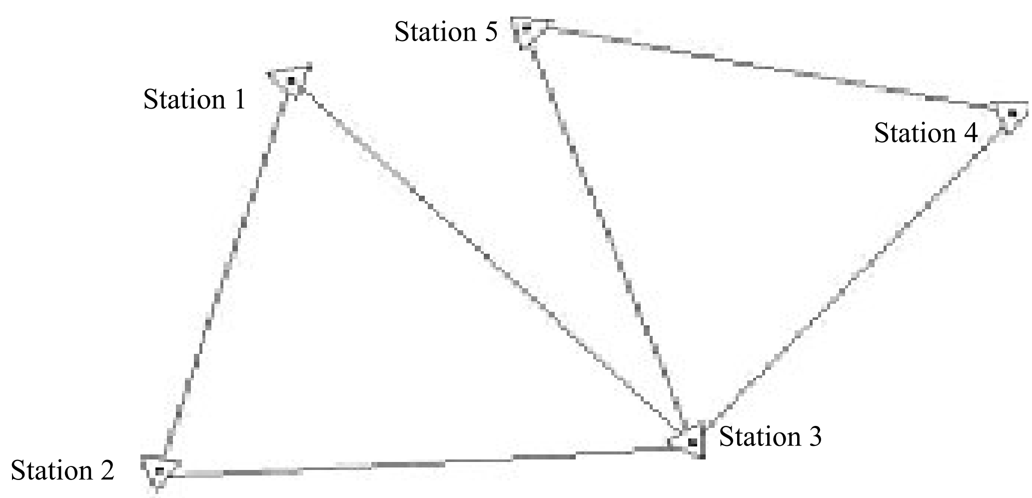


Figure 6A-2

6A.3-2 Satellite Geometry

Satellite geometry factors to consider when planning a GPS survey are:

- Number of satellites available
- Minimum elevation angle for satellites (elevation mask)
- Obstructions limiting satellite visibility
- Positional Dilution of Precision (PDOP)
- Vertical Dilution of Precision (VDOP) when performing vertical GPS surveys

Refer to tables 6A-1 through 6A-5 for specific requirements.

6A.3-3 Field Procedures

Reconnaissance

Proper field reconnaissance is essential to the execution of efficient, effective GPS surveys. Reconnaissance should include:

- Station setting or recovery
- Checks for obstructions and multipath potential
- Preparation of station descriptions (monument description, to-reach descriptions, etc.)
- Development of a realistic observation schedule

Station Site Selection

The most important factor for determining GPS station location is the project's requirements (needs). After project requirements, consideration must be given to the following limitations of GPS:

- Stations should be situated in locations, which are relatively free from horizon obstructions. In general, a clear view of the sky is required. Satellite signals do not penetrate metal, buildings, or trees and are susceptible to signal delay errors when passing through leaves, glass, plastic and other materials.
- Locations near strong radio transmissions should be avoided because radio frequency transmitters, including cellular phone equipment, may disturb satellite signal reception.
- Avoid locating stations near large flat surfaces such as buildings, large signs, fences, etc., as satellite signals may be reflected off these surfaces causing multipath errors.

With proper planning, some obstructions near a GPS station may be acceptable. For example, station occupation times may be extended to compensate for obstructions.

Weather Conditions

Generally, weather conditions do not affect GPS survey procedures with the following exceptions:

- GPS observations should never be conducted during electrical storms.
- Significant changes in weather or unusual weather conditions should be noted in the observation log (field notes). Horizontal GPS surveys should generally be avoided during periods of significant weather changes. Vertical GPS surveys should not be attempted during these periods.

Antenna Height Measurements

Blunders in antenna height measurements are a common source of error in GPS surveys because all GPS surveys are three-dimensional whether the vertical component will be used or not. Antenna height measurements determine the height from the survey monument mark to the phase center of the GPS antenna. With the exception of fixed-height tripods and permanently mounted GPS antennas, independent antenna heights shall be measured in both feet and meters (use conversion between feet and meters as a check) at the beginning and end of each observation session. A height hook or slant rod shall be used to make these measurements. All antenna height measurements shall be recorded on the observation log sheet and entered in the receiver data file. Antenna height measurements in both feet and meters shall check to within ± 0.01 feet. When a station is occupied during two or more observation sessions back to back, the antenna/tripod shall be broken down, reset, and re-plumbed between sessions. When adjustable antenna staffs are used (e.g., kinematic surveys), they should be adjusted so that the body of the person holding the staff does not act as an obstruction. The antenna height for staffs in extended positions shall be checked continually throughout each day. When fixed-height tripods are used, verify the height of the tripod and components (antenna) at the beginning of the project.

Documentation

The final GPS Survey project file should include the following information:

- Project report
- Project sketch or map showing independent baselines used to create the network
- Station descriptions
- Station obstruction diagrams
- Observation logs
- Raw GPS observation (tracking) data files
- Baseline processing results
- Loop closures
- Repeat baseline analysis
- Least squares unconstrained adjustment results
- Least squares constrained adjustment results
- Final coordinate list

For details regarding field notes and other survey records, see Chapter 14, "Survey Records."

6A.3-4 Office Procedures

General

For first-order, second-order, and some third-order Post-Processed GPS surveys, raw GPS observation (tracking) data shall be collected and post processed for results and analysis. Post processing and analysis are required for first-order and second-order GPS surveys. The primary post-processed results that are analyzed are:

- Baseline processing results
- Loop closures
- Repeat baseline differences
- Results from least-squares network adjustments

Post-processing software shall be capable of producing relative-position coordinates and corresponding statistics which can be used in a three-dimensional least squares network adjustment. This software shall also allow analysis of loop closures and repeat baseline observations.

Loop Closure and Repeat Baseline Analysis

Loop closures and differences in repeat baselines are computed to check for blunders and to obtain initial estimates of the internal consistency of the GPS network. Tabulate and include loop closures and differences in repeat baselines in the project documentation. Failure of a baseline in a loop closure does not automatically mean that the baseline in question should be rejected but is an indication that a portion of the network requires additional analysis.

Least Squares Network Adjustment

An unconstrained (free) adjustment is performed, after blunders are removed from the network, to verify the baselines of the network. After a satisfactory standard deviation of unit weight (network reference factor) is achieved using realistic *a priori* error estimates, a constrained adjustment is performed. The constrained network adjustment fixes the coordinates of the known reference stations, thereby adjusting the network to the datum and epoch of the reference stations. A consistent control reference network (datum) and epoch shall be used for the constrained adjustment. The NGS Horizontal Time Dependent Positioning (HTDP) program may be used to translate geodetic positions from one epoch to another. For details on epochs see Section 4.1-3, “NAD83 Epochs.” For details regarding least squares adjustments, refer to Section 5.4, “Least Squares Adjustment.”

6A.4 Order B (Caltrans) GPS Surveys

6A.4-1 Applications

High Precision Geodetic Network (HPGN) Surveys

HPGN surveys establish high-accuracy geodetic control stations along transportation corridors. HPGN and related stations are part of the California Spatial Reference System-Horizontal (CSRS-H) and the NGS National Spatial Reference System (NSRS).

6A.4-2 Specifications

HPGN surveys are performed using Order B specifications published by the FGCS. All HPGN surveys are planned and coordinated through the Office of Land Surveys and submitted to NGS.

6A.5 First-order (Horizontal) GPS Surveys

6A.5-1 Applications

Horizontal Corridor Control (HPGN-D) Surveys

First-order Horizontal Corridor Control Surveys shall be submitted to NGS for inclusion in the NSRS at the discretion of the District Surveys Engineer. Horizontal Corridor Control Surveys submitted to NGS are performed to FGCS first-order specifications with a 1:100,000 linear accuracy standard. For details, see Section 9.4-2, "Horizontal Corridor Control (HPGN-D) Surveys."

Project Control Surveys

First-order accuracy standards are preferred for horizontal Project Control Surveys. See Section 9.4-3, "Horizontal Project Control Surveys."

6A.5-2 Specifications

Methods

- Static
- Fast- static

Generally, static GPS survey methods are employed when baseline lengths are greater than 12 miles. Dual-frequency receivers are required for observing baselines over 9 miles in length. During periods of intense solar activity, dual frequency receivers shall be used for observing baselines over 6 miles in length. Table 6A-1 lists the specifications for first-order accuracy using static and fast-static GPS procedures.

Table 6A-1 First-order (Horizontal) GPS Survey Specifications

Specification	Static	Fast-static
General Network Design		
Minimum number of reference stations to control the project (1)	3 first-order (horz.) or better	3 first-order (horz.) or better
Maximum distance between the survey project boundary and network reference control stations	30 miles	30 miles
Location of reference network control (relative to center of project); minimum number of "quadrants," not less than	3	3
Minimum percentage of all baselines contained in a loop	100%	100%
Direct connection between survey stations which are closer than 20 percent of the distance between those stations traced along existing or new connections (adjacent station rule)	Yes	Yes
Minimum percentage of repeat independent baselines	5% of total	5% of total
Minimum number of independent occupations per station	100% (2 times) 10% (3 or more times)	100% (2 times) 10% (3 or more times)
Direct connection between intervisible azimuth pairs	Yes	Yes
Field		
Maximum PDOP during station occupation	5 (75% of time)	5
Minimum observation time on station	30 minutes	15 minutes
Minimum number of satellites observed simultaneously at all stations	5 (75% of time)	5
Maximum epoch interval for data sampling	15 seconds	10 seconds
Minimum time between repeat station observations	60 minutes	60 minutes
Antenna height measurements in feet and meters at beginning and end of each session (2)	Yes	Yes
Minimum satellite mask angle above the horizon (3)	10 degrees	10 degrees

Continued

Table 6A-1, Continued

Specification **Office**	**Static**	**Fast-static**
Fixed integer solution required for all baselines	Yes	Yes
Ephemeris	Precise	Precise
Initial position: maximum 3-d position error for the initial station in any baseline solution	33 feet	33 feet
Loop closure analyses, maximum number of baselines per loop	6	6
Maximum loop length	60 miles	60 miles
Maximum misclosure per loop, in terms of loop length	10 ppm	10 ppm
Maximum misclosure per loop in any one component (x, y, z) not to exceed	0.15 feet	0.15 feet
Repeat baseline length not to exceed	30 miles	30 miles
Repeat baseline difference in any one component (x, y, z) not to exceed	10 ppm	10 ppm
Maximum length misclosure allowed for a baseline in a properly-weighted, least squares network adjustment	10 ppm	10 ppm
Maximum allowable residual in any one component (x, y, z) in a properly-weighted, least squares network adjustment	0.01 feet	0.01 feet

Notes:

1. Network independent baselines are required to all "existing first-order (or better) GPS-established NSRS stations" located within 6 miles of the project exterior boundary.
2. Antenna height measurements are not required when using fixed-height antenna poles.
3. During office processing, start with a 15-degree mask. If necessary, the angle may be lowered to 10 degrees.

6A.6 Second-order (Horizontal) GPS Surveys

6A.6-1 Applications

Project Control Surveys

Second-order accuracy standards are acceptable for horizontal Project Control Surveys, although first-order accuracy standards are preferred. See Section 9.4-3, "Horizontal Project Control Surveys."

6A.6-2 Specifications

Methods

- Static
- Fast-static

Dual-frequency receivers are required for observing baselines over 9 miles in length. During periods of intense solar activity, dual frequency receivers shall be used for observing baselines over 6 miles in length. Table 6A-2 lists the specifications for second-order accuracy using static and fast-static GPS procedures.

Table 6A-2 Second-order (Horizontal) GPS Survey Specifications

Specification	Static	Fast-static
General		
Minimum number of reference stations to control the project (1)	3 second-order (horz.) or better	3 second-order (horz.) or better
Maximum distance between the survey project boundary and network reference control stations	30 miles	30 miles
Location of reference network control (relative to center of project); minimum number of "quadrants," not less than	3	3
Minimum percentage of all baselines contained in a loop	100%	100%
Direct connection between survey stations which are closer than 20 percent of the distance between those stations traced along existing or new connections (adjacent station rule)	Yes	Yes
Minimum percentage of repeat independent baselines	5% of total	5% of total
Minimum number of independent occupations per station	100% (2 times) 10% (3 or more times)	100% (2 times) 10% (3 or more times)
Direct connection between intervisible azimuth pairs:	Yes	Yes
Field		
Maximum PDOP during station occupation	5 (75% of time)	5
Minimum observation time on station	20 minutes	10 minutes
Minimum number of satellites observed simultaneously at all stations	5 (75% of time)	5
Maximum epoch interval for data sampling	15 seconds	10 seconds
Time between repeat station observations	45 minutes	45 minutes
Antenna height measurements in feet and meters at beginning and end of each session (2)	Yes	Yes
Minimum satellite mask angle above the horizon (3)	10 degrees	10 degrees

Continued

Table 6A-2, Continued

Specification	Static	Fast-static
Office		
Fixed integer solution required for all baselines	Yes	Yes
Ephemeris (4)	Broadcast	Broadcast
Initial position: maximum 3-d position error for the initial station in any baseline solution	66 feet	66 feet
Loop closure analyses, maximum number of baselines per loop	8	8
Maximum loop length	45 miles	45 miles
Maximum misclosure per loop, in terms of loop length	50 ppm	50 ppm
Maximum misclosure per loop in any one component (x, y, z) not to exceed	0.26 feet	0.26 feet
Repeat baseline length not to exceed	30 miles	30 miles
Repeat baseline difference in any one component (x, y, z) not to exceed	50 ppm	50 ppm
Maximum length misclosure allowed for a baseline in a properly-weighted, least squares network adjustment	50 ppm	50 ppm
Maximum allowable residual in any one component (x, y, z) in a properly-weighted, least squares network adjustment	0.26 feet	0.26 feet

Notes:

1. Network independent baselines are required to all “existing first-order (or better) GPS-established NSRS stations” located within 6 miles of the project exterior boundary.
2. Antenna height measurements are not required when using fixed-height antenna poles.
3. During office processing, start with a 15-degree mask. If necessary, the angle may be lowered to 10 degrees.
4. Precise ephemeris may be used.

6A.7 Third-order (Horizontal) GPS Surveys

6A.7-1 Applications

Third-order horizontal accuracy is acceptable for the following typical Caltrans survey operations:

- Supplemental control for engineering and construction surveys
- Photogrammetry control
- Controlling land net points
- Construction survey setup points for radial stakeout
- Setup points for engineering and topographic survey data collection
- Controlling stakes for major structures
- Monumentation surveys

6A.7-2 Specifications

Methods

- Static
- Fast-static
- Kinematic

Table 6A-3 lists the specifications for third-order accuracy using static, fast-static and kinematic GPS procedures.

Table 6A-3 Third-order (Horizontal) GPS Survey Specifications

Specification	Static	Fast-static	Kinematic
General			
Minimum number of reference stations to control the project (1)	3 third-order (horz.) or better	3 third-order (horz.) or better	3 third-order (horz.) or better
Maximum distance between the survey project boundary and network control stations	30 miles	30 miles	30 miles
Location of reference network control (relative to center of project); minimum number of "quadrants," not less than	2	2	2
Minimum percentage of all baselines contained in a loop	50%	50%	50%
Direct connection between survey stations which are less than 20 percent of the distance between those stations traced along existing or new connections (adjacent station rule)	No	No	No
Minimum percentage of repeat independent baselines	5%	5%	5%
Percent of stations occupied 2 or more times	75%	75%	100%
Direct connection between intervisible azimuth pairs	No	No	No
Field			
Maximum PDOP during station occupation	5 (75% of time)	5	5
Minimum observation time on station	30 minutes	5 minutes	5 Epochs
Minimum number of satellites observed simultaneously at all stations	4 (75% of time)	5	5 (100% of time)
Maximum epoch interval for data sampling	15 seconds	10 seconds	1 - 15 seconds
Minimum time between repeat station observations	20 minutes	20 minutes	20 minutes
Antenna height measurements in feet and meters at beginning and end of each session (2)	Yes	Yes	Yes
Minimum satellite mask angle above the horizon (3)	10 degrees	10 degrees	10 degrees

Continued

Table 6A-3, Continued

Specification **Office**	Static	Fast-static	Kinematic
Fixed integer solution required for all baselines	No	No	No
Ephemeris (4)	Broadcast	Broadcast	Broadcast
Initial position: max. 3-d position error for the initial station in any baseline solution	330 feet	330 feet	330 feet
Loop closure analyses, maximum number of baselines per loop	12	12	12
Maximum loop length	30 miles	30 miles	30 miles
Maximum misclosure per loop, in terms of loop length	100 ppm	100 ppm	100 ppm
Maximum misclosure per loop in any one component (x, y, z) not to exceed	0.03 feet	0.03 feet	0.03 feet
Repeat baseline length not to exceed	6 miles	6 miles	6 miles
Repeat baseline difference in any one component (x, y, z) not to exceed	100 ppm	100 ppm	100 ppm
Maximum length misclosure allowed for a baseline in a properly-weighted, least squares network adjustment	100 ppm	100 ppm	100 ppm
Maximum allowable residual in any one component (x, y, z) in a properly-weighted, least squares network adjustment	0.03 feet	0.03 feet	0.03 feet

Notes:

1. Network independent baselines are required to existing first-order (or better) GPS-established NSRS stations within 3 miles of the project exterior boundary.
2. Antenna height measurements are not required if fixed-height antenna tripods or poles are used.
3. During office processing, start with a 15-degree mask. If necessary, the angle may be lowered to 10 degrees.
4. Precise ephemeris may be used.

6A.8 Caltrans General-Order (Horizontal and Vertical) Post Processed GPS Survey Specifications

6A.8-1 Applications

General-order horizontal accuracy is acceptable for the following typical Caltrans survey operations:

- Collection of topographic and planimetric data
- Supplemental design data surveys; e.g., borrow pits, utility, drainage, etc.
- Construction staking
- Environmental surveys
- Geographic Information System (GIS) surveys.

6A.8-2 Specifications

Method

- Kinematic

Table 6A-4 lists the specifications for general-order accuracy using kinematic GPS procedures.

Table 6A-4 General-order (Horizontal) GPS Survey Specifications

Specification	Kinematic
Minimum number of reference stations to control the project	3 third-order or better
Minimum number of check stations	2
Maximum distance between the survey project boundary and the network reference control stations	6 miles
Maximum PDOP during station occupation	5
Minimum observation time on station	5 epochs
Minimum number of satellites observed simultaneously at all stations	5 (100% of time)
Maximum epoch interval for data sampling	1 – 15 seconds
Minimum satellite mask angle above the horizon	10 degrees (1)

Note:

1. During office processing, start with a 15-degree mask. If necessary, the angle may be lowered to 10 degrees.

6A.9 Vertical GPS Surveys

6A.9-1 General

The following guidelines are intended for use on local transportation projects, and are not applicable to larger area networks.

Introduction

Because vertical positioning techniques using GPS are still under development, the guidelines described in this section are preliminary and will be updated as improved techniques and procedures are developed. GPS-derived orthometric heights (elevations) are compiled from ellipsoid heights (determined by GPS observations) and modeled geoid heights (using an acceptable geoid height model for the area). See Figure 6A-3. (For more detail see Section 4.2, “Vertical Datum.”)

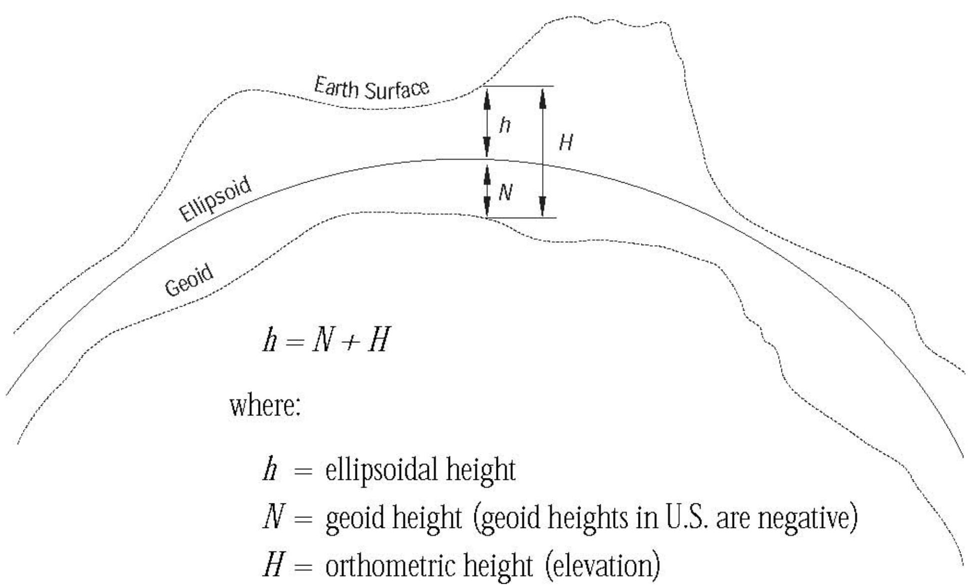


Figure 6A-3

Because of distortions in vertical control networks and systematic errors in geoid height models, results can be difficult to validate; however, results comparable to those obtained using differential leveling techniques are obtainable.

Geoid Height Modeling Methods

Two basic geoid modeling methods are used to develop the geoid heights:

- **Published National and Regional Geoid Models:** For relatively large areas (areas exceeding 6 miles by 6 miles), geoid heights shall be determined using the applicable national or regional geoid model published by NGS. Generally, the latest published model should be used. If there are indications that the existing published geoid model does not provide adequate geoid heights, the procedures listed in the following paragraph may be substituted.
- **Local Geoid Models Based on Existing Vertical Control:** For smaller areas, where the published geoid model proves inadequate and which contain sufficient existing vertical control stations, a local geoid model applicable to the specific survey can be developed based on the available vertical control. With this method, geoid heights are determined at new stations by interpolating between the geoid heights at the known vertical control stations. The interpolation can be accomplished automatically during the least squares adjustment process by entering the known orthometric heights as *ellipsoid* heights for each vertical control station in the adjustment software. The horizontal positions may change slightly. The amount of change should be evaluated before deciding if separate adjustments need to be performed and documented. If an independent vertical adjustment is performed, it should include a minimum of constraints (one position) in the horizontal dimension.

Accuracy Standards

When performing vertical control work using conventional methods, accuracy is expressed as a proportional accuracy standard based on the loop or section length (See Chapter 5, "Accuracy Classifications and Standards"). GPS survey accuracies, both horizontal and vertical, are expressed in the form of allowable station positional variance. This variance is basically independent of the baseline lengths, although baseline lengths do affect procedures and the accuracies attainable. For horizontal GPS surveys, baseline proportional accuracies are computed during the adjustment process, so a comparison of positional and proportional accuracy standards is provided; but, for GPS vertical surveys, only station positional accuracies are obtainable. A comparable relative measure of accuracy based on baseline length is not readily available during the adjustment process. The GPS guidelines included in this section are designed to achieve an orthometric height accuracy standard of either 0.07 feet or 0.16 feet (whichever is applicable, depending on equipment and procedures used) at the 95 percent confidence level relative to the vertical control used for the survey. This means that 95 percent of the orthometric height determinations will be within plus or minus 0.07 feet or 0.16 feet of the "true" relative value, provided the network is designed with sufficient redundancy and validation checks.

6A.9-2 Applications

Vertical GPS survey methods are an emerging technology. This is particularly true where orthometric heights (elevations) rather than ellipsoid heights are required, as is the case for most Caltrans surveys. Factors to consider when evaluating the use of vertical GPS survey methods are:

- Accuracy requirements for the survey
- Equipment availability
- Distance between survey stations
- Survey station locations (sky view obstructions, etc.)
- Specifications to be employed for the vertical GPS survey
- Whether elevations or relative differences (over time) are required
- Time and resources required as compared to conventional surveys
- Availability and density of suitable reference control
- Future survey efforts in the vicinity

Vertical Project Control Surveys

GPS surveys may be an effective means to establish vertical control (e.g., NAVD88) for a Vertical Project Control Survey, providing the required third-order accuracy standard is achieved. The achievable accuracy standards will depend on the guidelines employed and the distance to the vertical reference control network. See Section 6A.9-3, “Guidelines.” Conventional leveling procedures are to be used for third-order accuracy ties of less than 3 miles. When GPS methods are used to establish vertical control for a Vertical Project Control Survey, the GPS-determined benchmarks throughout the project must be a minimum of 3 miles apart. Densification of the Vertical Project Control Survey will generally be performed by conventional leveling techniques because of the relatively short distance (less than 3 miles) between these stations.

Other Surveys

See list of possible applications under Section 6A.8-1, “Caltrans General-Order (Horizontal and Vertical) Post Processed GPS Survey Specifications.”

6A.9-3 Guidelines

Guidelines for vertical control surveys using GPS are similar to those for first-order GPS horizontal control surveys with additional requirements to limit the errors in GPS ellipsoid height determination. Guidelines for GPS vertical control surveys to achieve 0.07 feet and 0.16 feet accuracy standards, relative to existing vertical control are shown in Table 6A-5. In addition to the tabular specifications, the following guidelines are applicable for all GPS vertical control surveys. For complex areas (mountainous, lack of control, need for greater precision, and longer distances to good control), the NGS State Geodetic Advisor should be contacted to obtain the latest information and specifications for vertical GPS surveys.

Table 6A-5 Vertical GPS Survey Guidelines (local projects)

Positional Accuracy Standard – 0.07 feet and 0.16 feet *

Specification	0.07 feet	0.16 feet
General		
Minimum number of horizontal control stations for the project (latitude, longitude, ellipsoid height)	3 first-order (HPGN-D) or better	3 first-order (HPGN-D) or better
Location of horizontal control stations (relative to center of project); minimum number of "quadrants," not less than	3	3
Minimum number of vertical control stations (benchmarks) for the project	4 see "General Notes"	4 see "General Notes"
Location of vertical control stations (relative to center of project); minimum number of "quadrants," not less than	4	4
Maximum distance between project survey stations	6 miles (avg. 4 miles)	12 miles (avg. 7 miles)
Minimum percentage of all baselines contained in a loop	100%	100%
Minimum percentage of repeat independent baselines (adjacent station rule)	100% of total	100% of total
Field		
Dual frequency GPS receivers required	Yes	Yes
Maximum VDOP during station occupation	4	4
Minimum observation time per adjacent station baseline	30 minutes	(1)
Minimum number of satellites observed simultaneously at all stations	5	5
Maximum epoch interval for data sampling	15 seconds	5 seconds
Time between repeat station observations	see "General Notes"	see "General Notes"
Minimum satellite mask angle above the horizon	15 degrees	15 degrees
Fixed height antenna tripod required	Yes	Optional
Required number of receivers	3	3

** Relative to the existing vertical control*

Table 6A-5, Continued

Specification **Office**	**0.07 feet**	**0.16 feet**
Antenna height measurements in feet and meters at beginning and end of each session	N/A	Yes (2)
Fixed integer solution required for all baselines	Yes	Yes
Ephemeris	Precise	Precise
Initial position: maximum 3-d position error for the initial station in any baseline solution. See note 3 below.	33 feet	33 feet
Loop closure analysis, maximum number of baselines per loop	6	6
Maximum ellipsoid height difference for repeat baselines	0.07 feet	0.16 feet
Apply NGS geoid height model for areas greater than	6 x 6 miles	6 x 6 miles
Maximum RMS values of processed baselines (2σ)	0.05 feet (typically <0.03 feet)	0.05 feet (typically <0.03 feet

Notes:

1. Minimum time on adjacent station baselines shall ensure that all integers can be resolved and the root mean square error shall not exceed 0.05 feet.
2. Antenna height measurements are required at the beginning and end of each observation period and shall be made in both feet and meters (as a check) if fixed-height tripods are not used.
3. Start with HPGN-D stations.

6A.9-4 General Notes Observations:

Data shall be collected at the vertical control stations continuously and simultaneously with the new project survey station observations. Adjacent survey stations shall be observed simultaneously. Observations at the new project survey stations shall be continuous for the times specified and must be repeated on a different day and at a different time. The repeated observations on different days shall be completed either four hours before the starting time of the first day's observations or be completed four hours after the ending time of the first day's observations. See Table 6A-5.

Datums/Network/Epoch:

Reference stations shall be the same datum, included in (or adjusted to) one consistent geodetic network, and of the same epoch (or adjusted to the latest epoch), especially in areas of known or suspected subsidence. Reference stations shall have the most recent epoch NAD83 latitude, longitude and ellipsoidal height. Vertical control surveys in subsidence areas may require special procedures.

Vertical Control Stations:

Three vertical control stations (bench marks) determine the plane of the geoid but provide no redundancy. At least one additional vertical control station shall be included in the project to provide this redundancy. If possible, three additional vertical control stations shall be considered, especially in areas where there are changes in the slope of the geoid as shown on gravity anomaly maps or where there are significant changes in the slope of the terrain. Note that reference stations with published orthometric heights (elevations) may be considered as meeting the requirement for vertical control stations.

In addition to the requirement that the vertical control stations be located in three quadrants of the survey (see Table 6A-5), the vertical control stations and project survey stations shall be located, if possible, in areas where the gravity is changing the least; i.e., locations where the gravity maps have the widest separation between contours. (Gravity anomaly maps are available from the California Division of Mines and Geology.) Also, the vertical control stations shall be located so that the project survey stations are bracketed by the vertical control stations. Determining elevations through extrapolation outside the area encompassed by the reference stations should not be attempted.

Checks:

The elevation difference between adjacent survey stations should be checked by conventional leveling (differential or trigonometric) methods for 10 percent or two sections (whichever is greater) of the project survey baselines (i.e., pairs of adjacent survey stations). The procedures employed and quality of observations/measurements shall produce results that meet third-order standards.

6B Real Time Kinematic (RTK) GPS Survey Specifications

6B.1 Method

6B.1-1 Conventional (Single Base Station) RTK GPS Surveys

Conventional RTK GPS surveys are kinematic GPS surveys (Section 6A.1-3) that are performed with a data transfer link between a reference GPS unit (base station) and rover unit(s). The field survey is conducted like a kinematic survey, except measurement data from the base station is transmitted to the rover unit(s), enabling the rover unit(s) to compute position in real time. The derived solution is a product of a single baseline vector from the base station to the rover unit(s).

6B.1-2 Real Time Network RTK GPS Surveys

Real-time network RTK surveys are similar in principle to conventional RTK surveys. Instead of a single base station, however, there are several permanently mounted reference GPS units called Continuous Geodetic Positioning Stations (CGPS), a central computer system, and a data transfer link between the CGPS, the central computer system, and the rover. The CGPS send measurement data to the central computer system, which processes the data and monitors the integrity of the CGPS network. In some systems, the central computer accepts measurement data from the rover to refine the correction model based on rover position. The central computer either sends CGPS measurement data to the rover, or allows the rover to access to the CGPS measurement data. The method used to determine the position of the rover depends on the configuration of the various system components. The derived solution may be a product of a single baseline vector from a CGPS to the rover unit, or may be a multiple baseline solution resulting from a combined network solution. It behooves the Land Surveyor to understand the network processes being used, and how these processes may propagate errors in the results

Real-time network RTK specifications are currently under development.

6B.2 Equipment

A conventional RTK system consists of a base station, one or more rover units, and a data transfer link between the base station and the rover unit(s).

6B.2-1 Base Station Requirements

A base station is comprised of a GPS receiver, an antenna, and a tripod. The GPS receiver and the antenna shall be suitable for the specific survey as determined from the manufacturer's specifications. Tripod requirements are specified in Section 6B.3-3.

6B.2-2 Rover Unit Requirements

The rover unit is comprised of a GPS receiver, an antenna, and a rover pole. The GPS receiver and the antenna shall be suitable for the specific survey as determined from the manufacturer's specifications.

A rover antenna shall be identical (not including a ground plane, if used at the base station) to the base station antenna unless the firmware/software is able to accommodate antenna modeling of different antenna types.

Rover pole requirements are specified in Section 6B.3-3.

6B.2-3 Data Transfer Link

The data transfer link can be either a UHF/VHF radio link or a cellular telephone link. The data transfer link shall be capable of sending the base station's positional data, carrier phase information, and pseudo-range information from the base station to the rover unit. This information shall be sufficient to correct the rover unit's position to an accuracy that is appropriate for the type of survey being conducted.

If the data transfer link utilizes a UHF/VHF radio link with an output of greater than 1 watt, a Federal Communications Commission (FCC) license is required.

All FCC rules and regulations shall be adhered to when performing an RTK survey. These shall include but are not limited to the following:

- Title 47, Code of Federal Regulations (CFR) part 90, Section 173 (47 CFR 90.173): Obligates all licensees to cooperate in the shared use of channels.
- 47 CFR 90.403: Requires licensees to take precautions to avoid interference, which includes monitoring prior to transmission.
- 47 CFR 90.425: Requires that stations identify themselves prior to transmitting.

Voice users have primary authorization on the portion of the radio spectrum utilized for RTK surveying. Data transmission is authorized on a secondary and non-interfering basis to voice use.

Failure to comply with FCC regulations subjects the operator, and their employer, to fines, seizure of their surveying equipment, civil liability, and/or criminal prosecution. Failure to comply also jeopardizes the future use of RTK/GPS surveying by or for Caltrans.

6B.2-4 Miscellaneous Equipment Requirements

The RTK equipment shall be suitable for the work being done.

All RTK equipment shall be properly maintained and checked for accuracy. The accuracy checks shall be conducted before each survey or at a minimum of once a week to ensure valid survey results.

For details regarding equipment repair, adjustment, and maintenance refer to Chapter 3, "Survey Equipment."

6B.3 General RTK Survey Specifications

In a conventional RTK survey "radial" shots are observed from a fixed base station to a rover unit. A delta X, delta Y, and delta Z are produced from the base station to the rover unit on the WGS84 datum. From these values, coordinates of the points occupied by the rover unit are produced.

6B.3-1 Conventional RTK Survey Design

RTK survey design differs from static and fast static GPS survey design. With static and fast static GPS surveys, a network design method is used. See Section 6A.3-1, "Network Design," for more details on GPS network design. The following criteria shall be used for RTK survey design:

- The project area shall be "surrounded" and enclosed with RTK control stations. (See the definition of RTK control station below.)
- If the RTK control station is used for horizontal control, the RTK control station shall have horizontal coordinates that are on the same datum and epoch as the datum and epoch required for the project.
- If the RTK control station is used for vertical control, the RTK control station shall have a height that is on the same datum as the datum required for the project.
- All RTK control stations shall be included in a GPS site calibration. (See the end of this section for the definition of a GPS site calibration.)
- If the RTK equipment does not support the use of a GPS site calibration, the RTK control stations shall be used as check shots.
- For third order RTK surveys, each new station shall be occupied twice. The second occupation of a new station shall use a different base station location. If the new station is being elevated by RTK methods, the second occupation of the new station shall have a minimum of 3 different satellites in the satellite constellation. This is generally achieved by observing the second occupation at a time of day that is either 4 hours before or 4 hours after the time of day of the first occupation.
- Establish the new stations in areas where obstructions, electromagnetic fields, radio transmissions, and a multipath environment are minimized.
- Use the current geoid model when appropriate.

Definition: An **RTK control station** is a station used to control a survey that utilizes RTK methods. The station shall have either horizontal coordinates, a height, or both. The order of accuracy of the horizontal coordinates and the height shall be at least third-order.

Definition: A **GPS site calibration** establishes a relationship between the observed WGS84 coordinates and the known grid coordinates. This relationship is characterized by a translation, rotation, and scale factor for the horizontal coordinates and by an inclined plane for the heights. By applying a GPS site calibration to newly observed stations, local variations in a mapping projection are reduced and more accurate coordinates are produced from the RTK survey.

Note: A GPS site calibration can be produced from RTK observations, an "office calibration," or from a combination of both. If the RTK control stations were established by static or fast static GPS techniques, then an office calibration may be used.

The procedures for an office calibration are:

- Do a minimally constrained adjustment before normalization holding only one WGS84 latitude, longitude, and ellipsoid height fixed.
- The epoch of the fixed values shall correspond to the epoch of the final coordinates of the RTK survey.
- Associate the results of this minimally constrained adjustment with the final grid coordinates in a site calibration.

6B.3-2 Satellite Geometry

Satellite geometry affects both the horizontal coordinates and the heights in GPS/RTK surveys. The satellite geometry factors to be considered for RTK surveys are:

- Number of common satellites available at the base station and at the rover unit.
- Minimum elevation angle for the satellites (elevation mask).
- Positional Dilution of Precision (PDOP) or Geometric Dilution of Precision (GDOP).
- Vertical Dilution of Precision (VDOP).

Refer to tables 6B-1 and 6B-2 for specific requirements.

6B.3-3 Conventional RTK Field Procedures

Proper field procedures shall be followed in order to produce an effective RTK survey. For Third-order RTK Surveys, these procedures shall include:

- It is recommended that the base station occupy an RTK control station with known coordinates for horizontal RTK surveys and known heights for vertical RTK surveys.
- A fixed height tripod shall be used for the base station.
- A fixed height survey rod or a survey rod with locking pins shall be used for the rover pole. A tripod and a tribrach may also be used. If a fixed height survey rod or a survey rod with locking pins is not used, independent antenna height measurements are required at the beginning and ending of each setup and shall be made in both feet and meters (as a check). The antenna height measurements shall check to within ± 0.01 feet.
- A bipod/tripod shall be used with the rover unit's survey rod.
- The data transfer link shall be established.
- A minimum of five common satellites shall be observed by the base station and the rover unit(s).
- The rover unit(s) shall be initialized before collecting survey data.
- The initialization shall be a valid checked initialization.
- PDOP shall not exceed 5.
- Data shall be collected only when the root mean square (RMS) is less than 70 millicycles.
- A check shot shall be observed by the rover unit(s) immediately after the base station is set up and before the base station is taken down.
- The GPS site calibration shall have a maximum horizontal residual of 0.07 feet for each horizontal RTK control station.
- The GPS site calibration shall have a maximum vertical residual of 0.10 feet for each vertical RTK control station.
- The new stations shall be occupied for a minimum of 30 epochs of collected data.
- The precision of the measurement data shall have a value less than or equal to 0.03 feet horizontal and 0.03 feet vertical for each observed station.
- The rover unit(s) shall not be more than 6 miles from the base station.

- The second occupation of a new station shall have a maximum difference in coordinates from the first occupation of 0.07 feet.
- The second occupation of a new station shall have a maximum difference in height from the first occupation of 0.13 feet.
- When setting supplemental control by RTK methods for conventional surveys, it is recommended that the new control points be a minimum of 1000 feet from each other. See Chapter 5, "Accuracy Classifications and Standards," for minimum accuracy standards that shall be achieved for specific surveys.
- When establishing set-up points for conventional survey methods, set three intervisible points instead of just an "azimuth pair." (This allows the conventional surveyor a check shot.)

For general-order RTK surveys, these procedures shall include:

- It is recommended that the base station occupy an RTK control station with known coordinates for horizontal RTK surveys and known heights for vertical RTK surveys.
- Fixed height tripods are recommended for the base station. If fixed height tripods are not used, independent antenna height measurements are required at the beginning and ending of each setup and shall be made in both feet and meters (as a check). The antenna height measurements shall check to within ± 0.01 feet.
- A fixed height survey rod or a survey rod with locking pins shall be used for the rover poles. A tripod and tribrach may also be used. If a fixed height survey rod or a survey rod with locking pins is *not* used, independent antenna height measurements are required at the beginning and ending of each setup and shall be made in both feet and meters (as a check). The antenna height measurements shall check to within ± 0.01 feet.
- A bipod/tripod shall be used with the rover unit's survey rod.
- The data transfer link shall be established.
- A minimum of five common satellites shall be observed by the base station and the rover unit(s).
- The rover unit(s) shall be initialized before collecting survey data.
- The initialization shall be a valid checked initialization.
- PDOP shall not exceed 6.
- Data shall be collected only when the root mean square (RMS) is less than 70 millicycles.

A check shot shall be observed by the rover unit(s) immediately after the base station is set up and before the base station is taken down.

- The GPS site calibration shall have a maximum horizontal residual of 0.07 feet for each horizontal RTK control station.
- The GPS site calibration shall have a maximum vertical residual of 0.10 feet for each vertical RTK control station.
- The precision of the measurement data shall have a value less than or equal to 0.05 feet horizontal and 0.07 feet vertical for each observed station.
- The rover unit(s) shall not be more than 6 miles from the base station.

6B.3-4 Office Procedures

Proper office procedures must be followed in order to produce valid results. These procedures shall include:

- Review the downloaded field file for correctness and completeness.
- Check the antenna heights for correctness.
- Check the base station coordinates for correctness.
- Analyze all reports.
- Compare the different observations of the same stations to check for discrepancies.
- After all discrepancies are addressed, merge the observations.
- Analyze the final coordinates and the residuals for acceptance.

6B.3-5 General Notes

- At present, RTK surveys shall not be used for pavement elevation surveys or for staking major structures.
- If the data transfer link is unable to be established, the RTK survey may be performed with the intent of post processing the survey data.
- The data transfer link shall not "step on" any voice transmissions.
- If a radio (UHF/VHF) frequency is used for the data transfer link, it shall be checked for voice transmissions before use.
- The data transfer link shall employ a method for ensuring that the signal does not interfere with voice transmissions.

6B.4 Third-Order RTK Surveys

Applications

Third-order horizontal accuracy is acceptable for the following typical Caltrans RTK operations:

- Supplemental control for engineering surveys and construction surveys
- Photo control
- Controlling land net points
- Construction survey set-up points
- Topographic survey set-up points
- Monument surveys
- Monument surveys (set)

Third-order vertical accuracy is acceptable for the following typical Caltrans RTK operations:

- Supplemental control
- Photo control
- Construction survey set-up points
- Topographic survey set-up points

Table 6B-1 lists the specifications for third-order accuracy using RTK procedures.

Table 6B-1 Third-order RTK Survey Specifications

Specification **Field**	RTK Survey
Geometry of RTK control stations	Surround and enclose the RTK project
Minimum accuracy of RTK control stations	Third-order
Minimum number of horizontal RTK control stations for horizontal RTK surveys	4
Minimum number of vertical RTK control stations for vertical RTK surveys	5
Base station occupies an RTK control station	Recommended
Base station uses a fixed height tripod	Yes
Percent of data collected with a valid checked initialization	100 %
Maximum PDOP during station observation	5
Minimum number of satellites observed simultaneously	5
Maximum epoch interval for data sampling	5 seconds
Minimum satellite mask above the horizon	15 degrees
Maximum RMS during a station observation	70 millicycles
Minimum number of epochs of collected data for each observation	30
Horizontal precision of the measurement data for each observation	Less than or equal to 0.03 feet
Vertical precision of the measurement data for each observation	Less than or equal to 0.05 feet

Continued

Table 6B-1, Continued

Specification	RTK Survey
Maximum residual of the horizontal coordinates for the horizontal RTK control stations in the GPS calibration	0.07 feet
Maximum residual of the height for the vertical RTK control stations included in the GPS calibration	0.10 feet
Maximum distance from the base station to the rover unit(s)	6 miles
Percent of new stations occupied 2 or more times	100%
Percent of second occupations having a different base station	100%
Maximum difference in horizontal coordinates of the second occupation from the first occupation	0.07 feet
Maximum difference in height of the second occupation from the first occupation	0.13 feet
Establish stations to be used as conventional survey control in groups of 3	Yes
Office	
Check the data collector file for correctness and completeness	Yes
Check the base station WGS84 coordinates and ellipsoid height for correctness	Yes
Analyze the GPS site calibration for a high scale factor and high residuals	Yes
Compare check shots with the known values	Yes
Check all reports for high residuals	Yes

6B-4 General-Order RTK Surveys

6B.4-1 Applications

General-order accuracy is acceptable for the following typical Caltrans RTK operations:

- Topographic surveys (data points)
- Supplemental design data surveys
- Construction surveys (staked points) excluding major structure points and finish grade stakes
- Environmental surveys
- Geographic Information System (GIS) surveys

Table 6B-2 lists the specifications for general-order accuracy using RTK procedures.

Table 6B-2 General-order RTK Survey Specifications

Specification	RTK Survey
Field	
Geometry of RTK control stations	Surround and enclose the RTK project
Minimum accuracy of RTK control stations	Third-order
Minimum number of horizontal RTK control stations for horizontal RTK surveys	3
Minimum number of vertical RTK control stations for vertical RTK surveys	4
Base station occupies an RTK control station	Recommended

Continued

Table 6B-2, Continued

Specification	**RTK Survey**
Base station uses a fixed height tripod	Recommended
Percent of data collected with a valid checked initialization	100 %
Maximum PDOP during station observation	6
Minimum number of satellites observed simultaneously	5
Maximum epoch interval for data sampling	5 seconds
Minimum satellite mask above the horizon	13 degrees
Maximum RMS during station observation	70 millicycles
Horizontal precision of the measurement data for each observation	Less than or equal to 0.05 feet
Vertical precision of the measurement data for each observation	Less than or equal to 0.07 feet
Office	
Check the data collector file for correctness and completeness	Yes
Check the base station WGS84 coordinates and ellipsoid height for correctness	Yes
Analyze the RTK site calibration for a high scale factor and high residuals	Yes
Compare check shots with the known values	Yes
Check all reports for high residuals	Yes